

A Study on Wet Tropospheric Delay Error Estimation for the Navigation Signals over Indian Region

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The present work deals with the wet tropospheric delay estimation using the different models for navigation signals over the Indian region. Results from various mathematical models are analysed for saturation vapour pressure, partial vapour pressure, and wet delay estimation. The delay is estimated for four places in India which are spread at different geographical locations. It is observed that the Wexler model is more suitable for saturation vapour estimation. It shows that the difference between 0.00 to 0.25 mb with reference values throughout the year. Saturation vapour pressure which is derived using the Wexler model is further used for partial vapour pressure estimation. Four different models were used to estimate partial vapour pressure and Zyuring model is found more suitable among all. The partial vapour pressure values vary from 5 mb to 25 mb at different altitudes. The results of the Zyuring model is further used to derive wet tropospheric delay. It is found that Hopfield model provides difference of up to 4 mm in tropospheric delay, better than any other seven models results which are used for wet delay estimation. Tropospheric wet delay is observed more in daytime as compared to nighttime. From the analysis, it is found that the Hopfield model is more suitable for wet delay estimation and can be used for wet delay corrections in navigation signals for accurate position estimation.

Keywords: Wet tropospheric delay; Vapour pressure; Humidity; GNSS

1 Introduction

Various navigation constellations are available in space like the Global Positioning System (GPS), Global Navigation Satellite System (GLONASS), Galileo *etc.* India also developed its own navigation system namely IRNSS (Indian Regional Navigation Satellite System) or NavIC (Navigation with Indian Constellation) which provides signal in L5 and S bands. These constellations are used for precise positioning primarily. However, the signals received from these constellations are also used for various applications like retrieving precipitable water vapour (PWV) and other atmospheric studies. A Global Navigation Satellite System (GNSS) provides the precise geographical location of a stand-alone receiver and accurate timing information at the receiver location considering there is no obstruction in the line of sight of the GNSS signals. To calculate a receiver's exact location, the signal transit time is measured between the point of observation and a minimum of four different satellites whose positions are known. GNSS receiver receives a signal from each satellite and estimates the distances are called pseudo ranges. These pseudo ranges along with

precise satellites position are used to determine receiver location. The accuracy of the receiver's location is dependent on various factors like the number of satellites linked to the receiver, discrepancies in each satellite's atomic clocks, satellite ephemeris (orbit) *etc.* Errors can also be caused by interference in the radio signals provided by the ionosphere or the troposphere. Another source of error is the case of multipath which occurs when signals are reflected from objects such as trees or buildings which delay the signal before it reaches to receiver.

Variations in the atmospheric conditions influence the speed of GNSS signals causing multiple errors and delays. These occur at two different places in the Earth's atmosphere- the ionosphere and the troposphere. The major delay is caused in the ionosphere which lies at the altitude of 50 to 500 km above the surface of the Earth. The troposphere is one of the layers of the atmosphere which varies up to 50-60 kilometers starting from the earth's surface. The tropospheric delay is the delay measurement of electromagnetic radiation traveling from satellite to receiver caused due to the troposphere. This impact is more limited than ionospheric impacts, changes more rapidly, and is not frequency dependent. This delay is

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because of the presence of gases, aerosols, and water vapour present in the troposphere. The delay can be divided into two categories as known as the hydrostatic and wet delay. A hydrostatic delay is caused because of the presence of dry gases in the troposphere like Nitrogen, Oxygen, Argon, etc. and varies with the change in meteorological parameters like temperature, humidity, pressure, etc. Wet delay occurs due to the water vapour present in the troposphere. It can be observed that wet delay influences numerical weather prediction model variables, directly or indirectly¹⁻³. It is an important parameter of the atmosphere which requires a detailed and frequent study.

Tropospheric models use the latest information of meteorological data sets and estimate delay. Still, the errors with respect to altitude goes higher and vary up to several centimeters⁴. The Zenith tropospheric delay (ZTD) can be defined as the integrated refractivity along a vertical path in the atmosphere out of which the wet delay component is:

$$d_w^z = 10^{-6} \int_{H_0}^{\infty} [K_2' \frac{e}{T} + K_3 \frac{e}{T^2}] dH \quad \dots (1)$$

The refractivity N is the wet refractivity and is empirically related to standard meteorological variables as²⁵

$$N = K_2' \left(\frac{e}{T} \right) + K_3 \left(\frac{e}{T^2} \right) \quad \dots (2)$$

Where H - elevation (Km), e - partial pressure of water vapour (mb), T - absolute temperature (⁰K) and $K_2' = 64.79$ K/m, $K_3 = 3.776 * 10^5$ K²/mb are the constants which are empirically determined.

Various studies have been carried out on vapour pressure and tropospheric delay modeling and its applications. Smith gave the relationship between total precipitable water (TPW) and surface dew point⁵. F.W. Murray computed the saturation vapour pressure and discussed about the problems in its computation⁶. Hopfield presented a new model for the height profile of tropospheric refractivity and expressions for computing corrections for range data⁷. Saastamoinen contributed to the theory of atmospheric refraction and showed that the refractivity integral can be determined without detailed knowledge of the height distribution of the refractive index⁸. Callhan predicted tropospheric wet-component range error from surface measurements⁹. Bolton introduced a simplified procedure for the computation of the equivalent potential temperature

for a water saturation pseudo-adiabatic process¹⁰. Buck gave the new equations for computing vapour pressure and enhancement factor¹¹. Ifadis modeled the atmospheric delay for radio waves based on the elevation angle of the satellite¹². Askne and Nordius estimated the tropospheric delay for microwaves from surface weather data using a close-form model and numerical integration methods¹³. Niell provided Global mapping functions for the atmospheric delay at radio wavelengths which are very useful in case of surface meteorology data are not available¹⁴. Elgered *et al.* measured the regional atmospheric water vapour using the Swedish permanent GPS network and showed that it has an agreement with radiosonde water vapour within 1 mm RMS error¹⁵. Fang *et al.* have discussed systematic errors associated with geodetic inversion of tropospheric zenith delay parameters and addressed the problem of reducing systematic errors in GPS-derived water vapour estimates⁴. Mendes and Langley discussed tropospheric zenith delay prediction accuracy for airborne GPS high-precision positioning in their work¹⁶. Dousa and Elias proposed an improved model for calculating tropospheric wet delay and its vertical approximation derived from the original meteorological data profiles¹⁷. Rózsa modeled tropospheric delays using the global surface meteorological parameter model GPT2 and showed that the GPT2 helped to remove more than 90% of the bias in tropospheric delay found in the RTCA model¹⁸. Chen has done a comprehensive evaluation and analysis of the water vapor tomographic performance using multi-source data in the China region¹⁹. Yonus has modeled for wet tropospheric delay error using the 1092 radio soundings and estimated precipitable water vapour content in Egypt²⁰. Since a lot of studies have been done for the estimation of vapour pressure and wet delay estimation through various models at different locations, such studies are limited over the Indian regions and also a comparative assessment is required to investigate more suitable models for vapour pressure and wet delay estimation over the region.

In the present study, an analysis is carried out on saturation vapour pressure, the vertical profiles of partial vapour pressure, and zenith wet tropospheric delays. The objective of the current study is to find a more suitable model for the estimation of these parameters under variable atmospheric conditions over the Indian region. This study is carried out

using AWS data from different stations of India representing the North, South, East, and West parts of the country. At the end of the analysis, more suitable models are predicted for the estimation of wet tropospheric delay and partial vapour pressure over the region. This study is very well supported by the statistical analysis at the different stages to find a more appropriate model.

2 Data Description

Daily Meteorological data set from January to December was collected from the Meteorological & Oceanographic Satellite Data Archival Centre (MOSDAC) for the year 2017. This portal provides the instrumental meteorological data from the Automated Weather Station (AWS) located at various places along with the satellite observations. The study is carried out using four different stations dataset namely Dehradun, Ahmedabad, Cuddalore, and Karimganj, representing different geography and atmospheric conditions (Fig. 1). The coordinates and altitudes of these stations are given in Table 1. Average monthly values are used for the analysis. This data includes temperature, pressure, relative humidity and rainfall at sea level which are available at every hour for these stations in India. Mean values are calculated separately for day and night to analyse the diurnal variations. The duration considered for day-time is 07:30 hours to 19:30 hours and for night-time is 19:30 hours to 07:30 hours on the following

day. Any missing values were evaluated using estimation from the previous and following days by the general averaging method.

3 Methodology

3.1 Surface Humidity Estimation

The hourly readings are used to estimate the monthly mean of temperature and relative humidity for both day and night. First the suitable model to estimate saturation vapour pressure (e_s) which depends on the temperature, is investigated for further estimation of partial vapour pressure. The partial vapour pressure (e) was estimated using the following relation:

$$e = e_s * \frac{R}{100} \quad \dots (3)$$

where e - partial vapour pressure (mb), e_s - saturation vapour pressure (mb), R - relative humidity.

Under this objective, the Tetens's, Magnus', Buck's, Wexler's, Bolton's and Goff-Gratch's models were used for saturation vapour pressure estimation and further these were evaluated and compared with

Table 1 — AWS stations coordinates

Station	Latitude(°N)	Longitude(°E)	Altitude (m)
Dehradun	30.31	78.30	650
Ahmedabad	72.57	23.02	53
Cuddalore	11.74	79.77	4.6
Karimganj	24.60	92.38	24

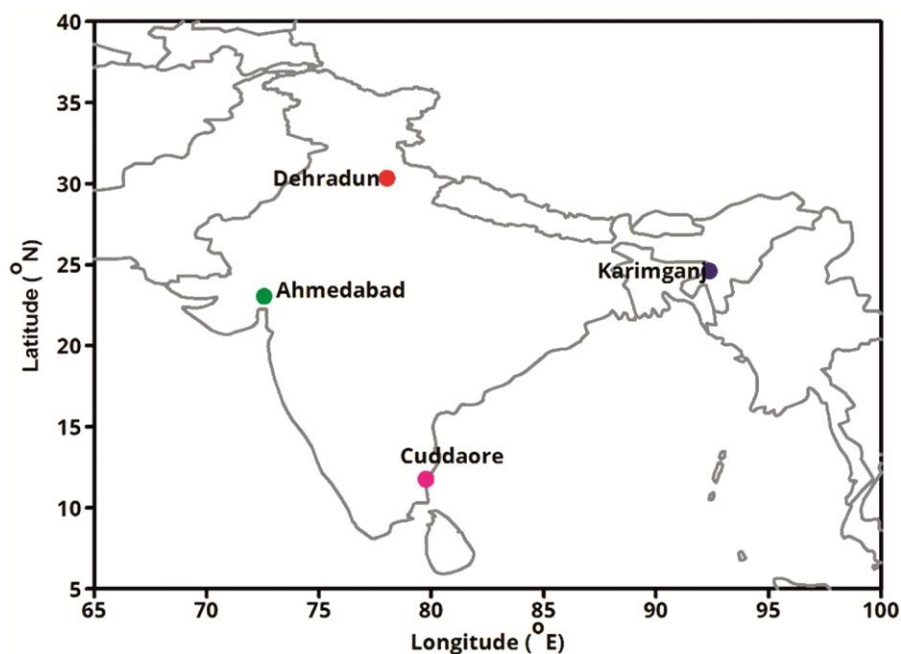


Fig. 1 — AWS locations over India

reference values. Partial vapour pressure is also estimated from saturation vapour pressure and relative humidity using Eq. 3. The reference values are estimated using the dew point method. Following equations from different models are used to estimate saturation vapour pressure (e_s):

Teten’s Model²¹

$$e_s(t) = 6.11 X e^{\left[\frac{17.27t}{t+237.3}\right]} \quad \dots (4)$$

Given $-50^\circ\text{C} \leq t \leq 50^\circ\text{C}$.

Magnus Model⁶

$$e_s(t) = 6.11 X 10^{\left[\frac{7.45t}{237.3+t}\right]} \quad \dots (5)$$

Given $t \geq 0^\circ\text{C}$.

Buck’s Model¹¹

$$e_s(t) = 6.1121 X e^{\left[\frac{(18.678 - \frac{t}{234.5})t}{257.14 + t}\right]} \quad \dots (6)$$

Given $t > 0^\circ\text{C}$.

Wexler’s Model²²

$$e_s(Wex) = 0.01. e^{\left[+0.17838301 X 10^{-4}T^2 - 0.84150417 X 10^{-9}T^3 + 0.44412543 X 10^{-12}T^4 + 2.858487 \ln T\right]} \quad \dots (7)$$

Bolton’s Model¹⁰

$$e_s = 6.112 X e^{\left[\frac{17.67(T-273.16)}{T-29.66}\right]} \quad \dots (8)$$

Goff Gratch’s Model²³

This model was evaluated using monthly mean temperature in °K such that $T > 273.16^\circ\text{K}$.

$$\log_{10}[e_s(T)] = a_1 \left[\frac{373.16}{T} - 1\right] + b_1 \log_{10} \left[\frac{373.16}{T}\right] + c_1 \left[10^{d_1 \cdot \left(1 - \frac{T}{373.16}\right)} - 1\right] + e_1 \left[10^{f_1 \cdot \left(\frac{373.16}{T} - 1\right)} - 1\right] + \log_{10}(g_1) \quad \dots (9)$$

The value of coefficients is $a_1 = -7.90298$, $b_1 = 5.02808$, $c_1 = 1.3816 \times 10^{-7}$, $d_1 = 11.344$, $e_1 = 8.1328 \times 10^{-3}$, $g_1 = -3.49149$, $f_1 = 1013.246$. where t is the temperature in °C for Teten, Magnus and and Bucks models. T is in °K for the Bolton, Wexler and Goff–Gratch’s Model. Unit of e_s is mb for the Magnus, Buck, Wexler, Bolton and Goff–Gratch’s models. For the Teten’s model the unit is Kpa.

Dew Point Method

Obtained results of saturation vapour pressure and partial vapour pressure from the above methods are compared with the reference values obtained from the dew point method. First, the dew point temperature

(T_d) is estimated which requires relative humidity (R) and temperature (T in °C) using equation (10). Further, the actual vapour pressure (e) is estimated using equation (11) and the saturation vapour pressure (e_s) is estimated using Eq. 3.

$$T_d = T - [(14.55 + 0.114T)(1 - R) + [(2.5 + 0.007T)(1 - R)]^3 + (15.9 + 0.117T)(1 - R)^{14}] \quad \dots (10)$$

$$e = 6.11 X 10^{\left(\frac{7.5 X T_d}{237.3 + T_d}\right)} \quad \dots (11)$$

Further, the estimation of vapour pressure at different altitude, the pressure and temperature values are required at that level. These have been derived using following equations⁵:

The pressure value for isothermal layers like where temperature is constant, is given as:

$$P = P_0 e^{\left(-\frac{g_0 \phi}{R_d T_0}\right)} \quad \dots (12)$$

For other layers, pressure distribution with height is given as:

$$P = P_0 \left(\frac{T_0 - \beta \phi}{T_0}\right)^{\frac{g_0}{R_d \beta}} \quad \dots (13)$$

Temperature for these layers is estimated using linear interpolation technique¹⁶.

$$T = T_0 - \beta h \quad \dots (14)$$

where P_0 -surface pressure (mb), ϕ – geo potential height (km), β - temperature laps rate (°K/km), (h) is the height, T_0 - Surface temperature (K), R_d - gas constant (287.05 J.kg⁻¹.K⁻¹) and g_0 - surface gravity (m/s²).

3.2 Vertical Humidity Profile over India

Callhan, Zyuring and Askne and Nordius models are investigated to estimate water vapour pressure with heights depending on surface water vapour pressure. The difference between pressure levels can be kept minimum to ascertain the sufficient accuracy. The output of these models are used in height dependent models to derive wet tropospheric delay.

Callhan’s Model⁹

$$e = e_0. exp(-aH - bH^2) \quad \dots (15)$$

where $a = 0.248/ \text{km}$ and $b = 0.048/\text{km}^2$ are nominal values. H - height above the surface (Km).

Zyuring Model²⁴

$$e = e_0 10^{-\frac{H}{6} - \frac{H^2}{120}} = e_0 \exp(-0.3838H - 0.01919H^2) \quad \dots (16)$$

Where H - height above the surface (Km).

Askne and Nordius Model¹³

$$e = e_0 \left(\frac{T}{T_0}\right)^{\frac{\lambda' g}{R_d \beta}} \quad \dots (17)$$

$$e = e_0 \left(\frac{P}{P_0}\right)^{\lambda+1} \quad \dots (18)$$

Here P_0 , T_0 , and e_0 are pressure, temperature and water vapour pressure respectively at surface level. P , T and e are the pressure, temperature and water vapour pressure respectively at height H (Km). β is the temperature lapse rate. λ is the water vapour lapse rate.

3.3 Wet Tropospheric Delay Estimation

Further the wet tropospheric delay (d_w^z) models are investigated to estimate the tropospheric delay. These models use surface water vapour pressure (e_0) and temperature (T_0) to estimate wet delay. The contribution of zenith wet delay in total tropospheric delay is around 10% and this delay component depends on water vapour content, which is highly variable in the atmosphere and time¹⁶. The output of these models are compared with the results from numerical integration model (NIM).

Saastamoinen's Model⁸

Saastamoinen model is given as:

$$d_w^z = 0.002277 \left\{ \frac{1255}{T_0} + 0.05 \right\} e_0 \quad \dots (19)$$

Hopfield's Model⁷

$$d_w^z = 10^{-6} N_{wet} \frac{H_w}{5} \quad \dots (20)$$

where N_{wet} - wet refractivity at the surface, developed by Smith and Weintraub²⁵:

$$N_{wet} = 3.73 * 10^5 \frac{e_0}{T_0^2} \quad \dots (21)$$

where H_w - height of water vapour(Km),

Ifadis's Model¹²

$$d_w^z = 0.00554 - 0.880 * 10^{-4} (P_0 - 1000.0) + 0.272 * 10^{-4} e_0 + 2.771 \frac{e_0}{T_0} \quad \dots (22)$$

Here P_0 is pressure (mb).

Berman's Model²⁶

The zenith wet tropospheric delay model by BERMAN can be given as:

$$d_w^z = 10.946 * K \frac{e_0}{T_0} \quad \dots (23)$$

where $K = 0.3224$.

Mendes's Model¹⁶

$$d_w^z = 0.122 + 0.00943. e_0 \quad \dots (24)$$

MOPS's Model²⁷

In 1998, MOPS (Minimum Operational Performance Standards) estimated the zenith wet delay given as:

$$d_w^z = \frac{10^{-6}.k_3.R_d}{g_m.(\lambda+1)-\beta.R_d} \cdot \frac{e_0}{T_0} \quad \dots (25)$$

where β - temperature lapse rate (K/m), λ - partial vapour pressure lapse rate (mb/m). The values of constants are

$k_3 = 382000 \text{ K}^2 \text{ hPa}^{-1}$, $R_d = 287.054 \text{ J kg}^{-1} \text{ K}^{-1}$ and $g_m = 9.784 \text{ ms}^{-2}$.

Chao's Model²⁸

$$d_w^z = 4.70 * 10^2 \frac{e_0^{1.23}}{T_0^2} + 1.71 * 10^6 \frac{e_0^{1.46}}{T_0^3} \alpha \quad \dots (26)$$

where α is the temperature lapse rate.

Callhan's Model⁹

Callhan model is given as:

$$d_w^z = \frac{1035 e_0}{T_0^2} \quad \dots (27)$$

Numerical Integration Model (NIM)²⁰

The wet tropospheric delay is estimated using NIM technique by integrating the refractivity information as given by Eqs 1 & 2. Simpson's formula is used to solve numerical integration for estimation of wet tropospheric delay.

$$d_w^z = \frac{1}{6} \sum_{i=1}^{i=\frac{n}{2}} (H_{2i} - H_{2i-2}) (N_{w2i-2} + 4 * N_{w2i-1} + N_{w2i}) \quad \dots (28)$$

where i is the integration node number. Using Eq. 28 wet tropospheric delay is determined where the integration nodes are taken at an equal interval from earth surface to 14 km height as per the following criteria considering variable amount of vapour present from surface to top of the troposphere:

(1) Surface to 3 km delay is calculated at 50 m interval.

- (2) 3 - 7 km delay is calculated at 100 m interval.
- (3) 7 - 10 km delay is calculated at 200 m interval.
- (4) 10 - 14 km delay is calculated at 400 m interval.

4 Results and Discussion

Hourly data of temperature, relative humidity, and surface pressure are taken and converted into monthly mean values. The monthly mean values are calculated for the day and night separately to observe the diurnal effect. Fig. 2, shows the difference in saturation vapour pressure with the actual values for the Karimganj station. The figure shows that the difference varies from 0.00 to 0.23 mb throughout the year. The difference is observed slightly less in the

night as compared to day. In the monsoon session, higher differences are observed. Similarly, the variation in saturation vapour pressure for the other stations are observed. The differences vary from -0.2 to 0.4 mb for station Dehradun considering the different times of the year. The variation over station Ahmedabad shows that the differences range from -0.2 to 0.6 mb. In case of the variation for Cuddalore station, the differences vary from 0.0 to 0.6 mb. In all the cases the differences in night are observed less as compared to the day.

The mean error of saturation vapour pressure along with root mean square (RMS) errors are provided in Table 2 & 3 for day and night respectively. From

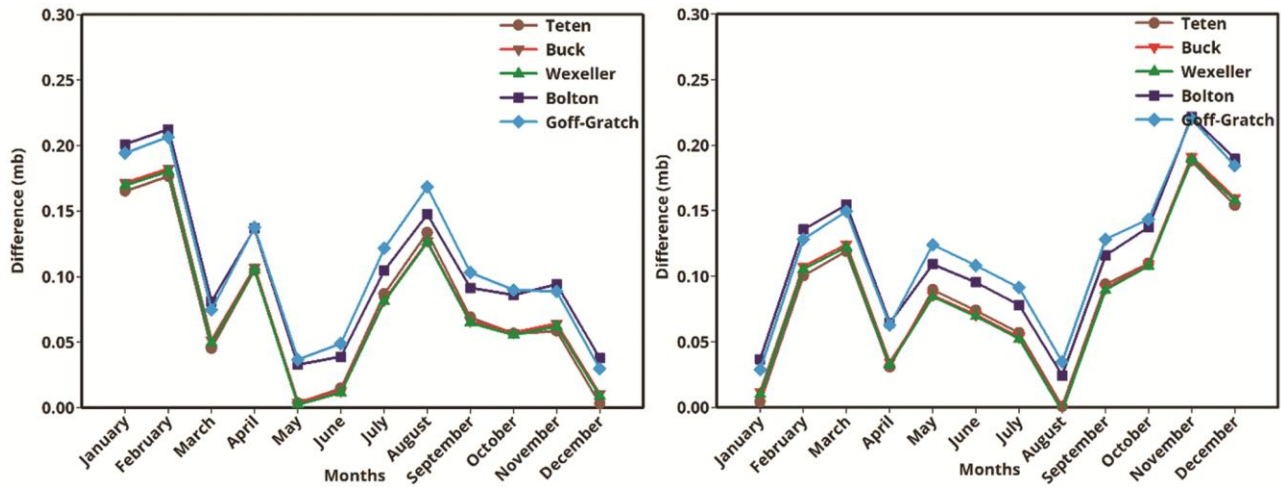


Fig. 2 — Difference in Saturation Vapour Pressure (mb) for Karimganj at Day Time (Left Panel) and Night Time (Right Panel)

Table 2 — Error statistics of various models in saturation vapour pressure (mb) estimation (Day time)

		Teten	Magnus	Buck	Wexler	Bolton	Goff-G.
DEHRADUN	Mean	0.0502	0.4090	0.0512	0.0497	0.0767	0.0813
	RMS	0.1448	0.4530	0.1453	0.1448	0.1560	0.1577
AHMEDABAD	Mean	0.0897	0.6014	0.0839	0.0836	0.0990	0.1233
	RMS	0.2279	0.6814	0.2256	0.2254	0.2335	0.2433
CUDDALORE	Mean	0.3201	0.8478	0.3142	0.3135	0.3335	0.3546
	RMS	0.3626	0.8945	0.3547	0.3545	0.3687	0.3938
KARIMGANJ	Mean	0.0764	0.4366	0.0781	0.0763	0.1054	0.1083
	RMS	0.0951	0.4548	0.0965	0.0951	0.1197	0.1221

Table 3 — Error statistics of various models in saturation vapour pressure (mb) estimation (Night Time)

		Teten	Magnus	Buck	Wexler	Bolton	Goff-G.
DEHRADUN	Mean	0.0373	0.2555	0.5893	0.0407	0.0681	0.0637
	RMS	0.0865	0.3032	0.6849	0.0873	0.1049	0.1037
AHMEDABAD	Mean	0.1716	0.5293	0.7650	0.1712	0.1984	0.2028
	RMS	0.2239	0.5979	1.0731	0.2208	0.2404	0.2501
CUDDALORE	Mean	0.1483	0.5705	0.6653	0.1460	0.1744	0.1818
	RMS	0.1852	0.5971	0.8050	0.1820	0.2039	0.2133
KARIMGANJ	Mean	0.0849	0.4490	0.0282	0.0846	0.1135	0.1168
	RMS	0.0101	0.4657	0.2931	0.0101	0.1267	0.1288

Table 2, it can be seen that the Wexler model gives the best performance over Indian conditions as it shows the minimum mean and RMS errors in all stations for daytime analysis. The mean errors of Wexler model vary from 0.0497 mb to 0.313 mb. The RMS error is varying from 0.095 mb to 0.354 mb. The errors are also estimated for nighttime and is represented in Table 3. It can be seen that for all the stations except Dehradun, the mean error shown using Wexler model is minimum which varies from 0.084 to 0.171. Though for Dehradun, the Teten model is giving minimum error but it is also close to Wexler model result. RMS error also follows the same pattern as followed by mean error. From Fig. 2 also it can be observed that the difference with actual values is less for the Wexler model however other models like the

Teten model, the Bolton model also have a very close approximation to the Wexler model. The results obtained using the Wexler model are used for the estimation of partial vapour pressure in daytime and nighttime for all stations.

Figure 3 represents the partial vapour pressure pattern estimated using saturation vapour pressure results for the station Karimganj. From Fig. 3, it is clearly shown that the Wexler model shows minimum error. Teten's also gives very close results to the Wexler model in this case. Similar results are obtained for other stations. Results obtained from the Magnus model are not presented in figures because of large variations.

Figure 4 represents the distribution of surface partial vapour pressure for all stations. The partial

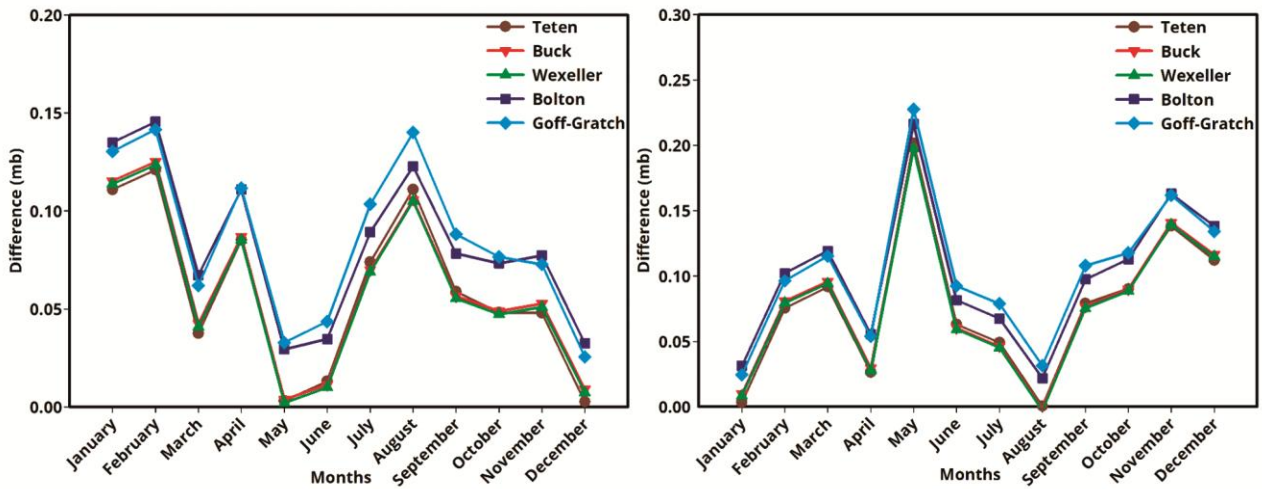


Fig. 3 — Difference in Partial Vapour Pressure (mb) for Karimganj at Day Time (Left Panel) and Night Time (Right Panel)

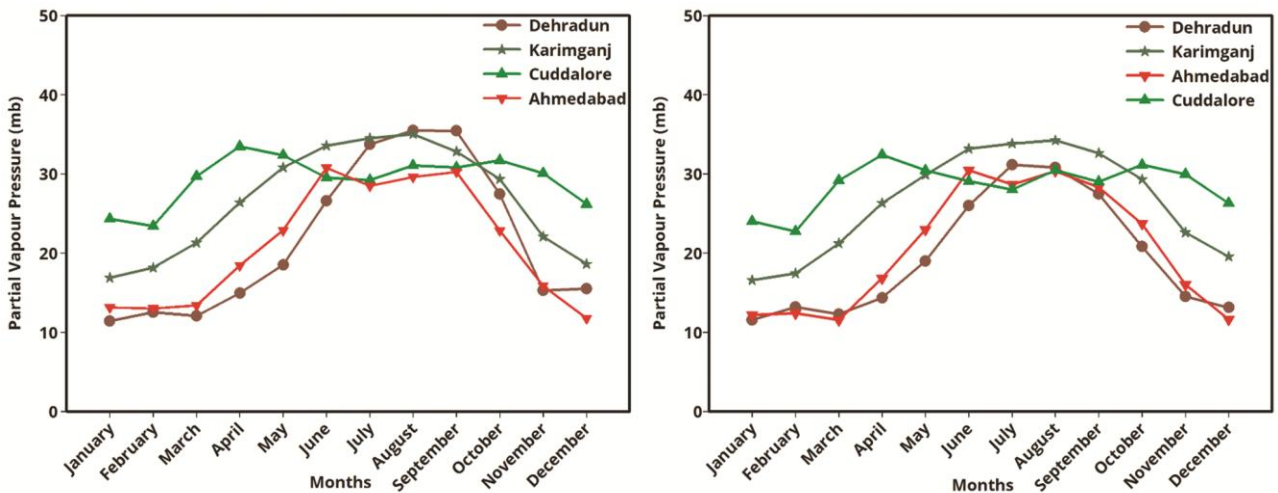


Fig. 4 — Distribution of surface partial vapour pressure (mb) over Indian Stations at Day Time (Left Panel) and Night Time (Right Panel)

vapour pressure is estimated using the Wexler model as discussed earlier. It is seen that from May to September partial vapour pressure is high which is going up to 40 mb approximately for all stations. Station Cuddalore does not show more variation and vapour pressures are estimated at around 30 mb throughout the year. The reason for this is that the station is situated in a coastal area where more humidity is observed throughout the year. For the daytime, this value is a little more as compared to the nighttime estimation. Station Dehradun shows the lowest partial vapour pressure in all sessions excluding the monsoon sessions in the daytime. In the monsoon session, the partial vapour pressure goes slightly high.

Table 4 presents the error statistics of various models to predict water vapour pressure with heights. From the table, it can be seen that Zyuring model has a minimum mean and RMS errors as compared to other models for all the stations when validated with partial water vapour vertical profile, derived using dew point method. This signature is observed for both day and night data. The monthly variation of the vertical profile of partial vapour pressure is given in the Figs. 5-8. Fig. 5 presents the analysis for station Dehradun, which shows that maximum partial vapour pressure is in September month close to 25 mb, if daytime data is considered while in night time maximum partial vapour pressure is shown in August month which is close to 20 mb. The minimum partial vapour pressure is observed in January in both the cases which is observed less than 10 mb. Over

Ahmedabad station, the maximum partial vapour pressure is observed in June for daytime and August for night time while minimum in December month as shown in Fig. 6. In Fig. 7 for station Cuddalore, very less variation is observed. As the station is very near to coastal area and has more humidity throughout the year over day and night, has very less change in partial vapour pressure. For station Karimganj, highest is observed in the month of August while the lowest is observed in January in the daytime as shown in Fig. 8. The maximum values are observed close to 25 mb and minimum values are observed close to 10 mb, considering the different cases. Partial vapour pressure value is varying from 5 mb to 25 mb, in all cases. The variation is more for Dehradun station and less for Cuddalore station. Callahan, Zyuring and Askne and Nordius (pressure-based) support the results with a slight variation. Askne and Nordius (temperature-based) estimated values are not presented in the figures because of large deviations. The complete statistics for analyzing best model is presented in Table 4.

Finally, the zenith wet tropospheric delay is estimated using for all the stations and its difference is estimated using the numerical integration technique (NIM). The differences are presented in Fig. 9 and statistics are given in Table 5 for day and night. From Fig., it is obvious that the differences of wet tropospheric delay estimated using the Hopfield model with numerical integration method show a close approximation. That means this model gives close results to the NIM values. For station Dehradun

Table 4 — Error statistics of various models in water vapour pressure (mb) estimation

		Day				Night			
		Callahan	Zyuring	Askne – Nordius(T)	Askne – Nordius(P)	Callahan	Zyuring	Askne – Nordius(T)	Askne – Nordius(P)
DEHRADUN	Mean	0.0035	0.0021	0.1935	0.0045	0.0021	0.0012	0.0779	0.0026
	RMS	0.0196	0.0115	0.3542	0.0250	0.0123	0.0070	0.2292	0.0157
AHMEDABAD	Mean	0.0065	0.0038	0.1399	0.0085	0.0108	0.0063	0.0542	0.0141
	RMS	0.0287	0.0164	0.2557	0.0368	0.0315	0.0180	0.2570	0.0404
CUDDALORE	Mean	0.0200	0.0117	0.2113	0.0261	0.0105	0.0071	0.1925	0.0156
	RMS	0.0512	0.0293	0.3565	0.0657	0.0293	0.0167	0.3285	0.0375
KARIMGANJ	Mean	0.0056	0.0033	0.1732	0.1790	0.0073	0.0043	0.1740	0.0094
	RMS	0.0155	0.0088	0.3048	0.0197	0.0204	0.0117	0.3048	0.0261

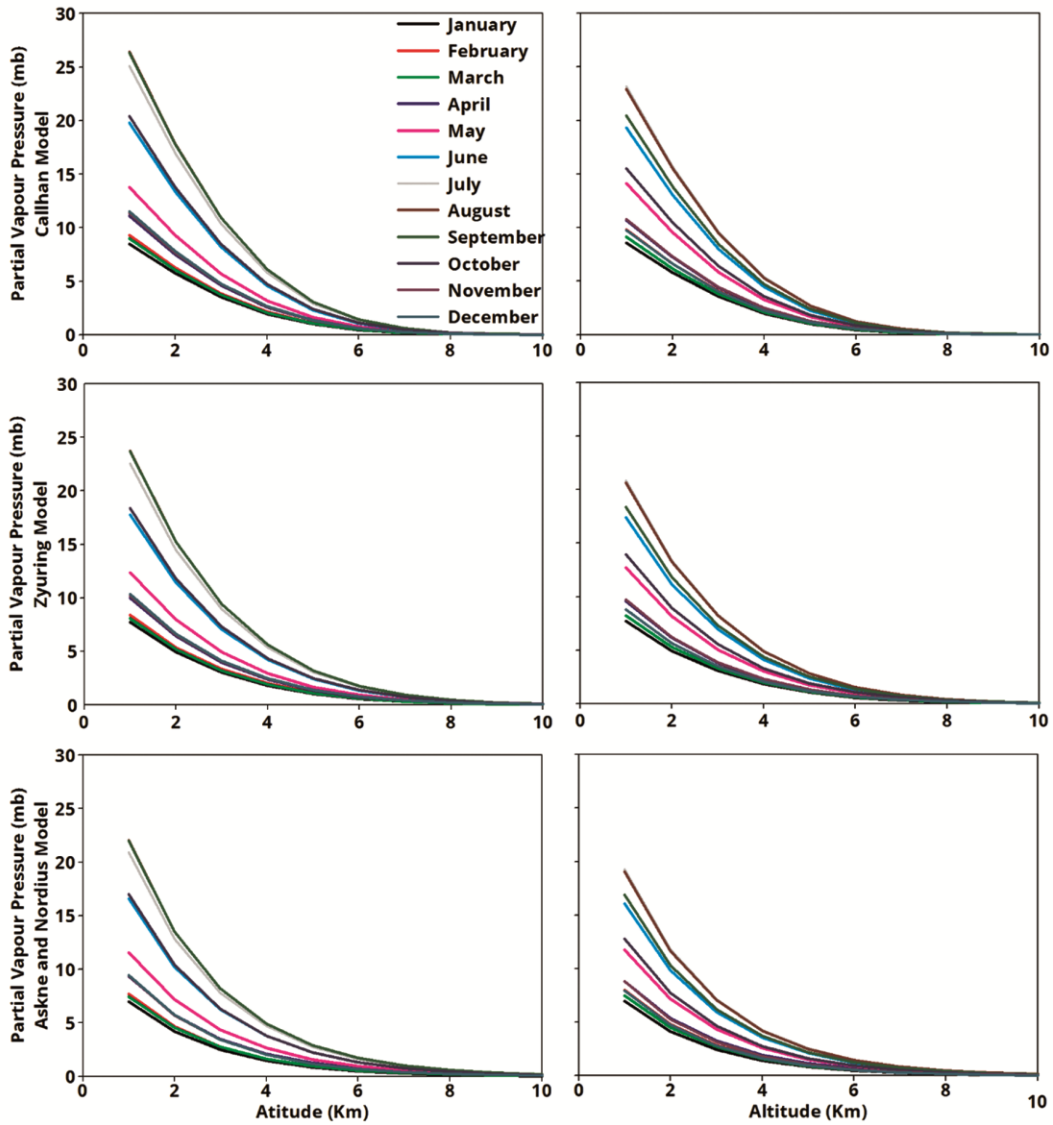
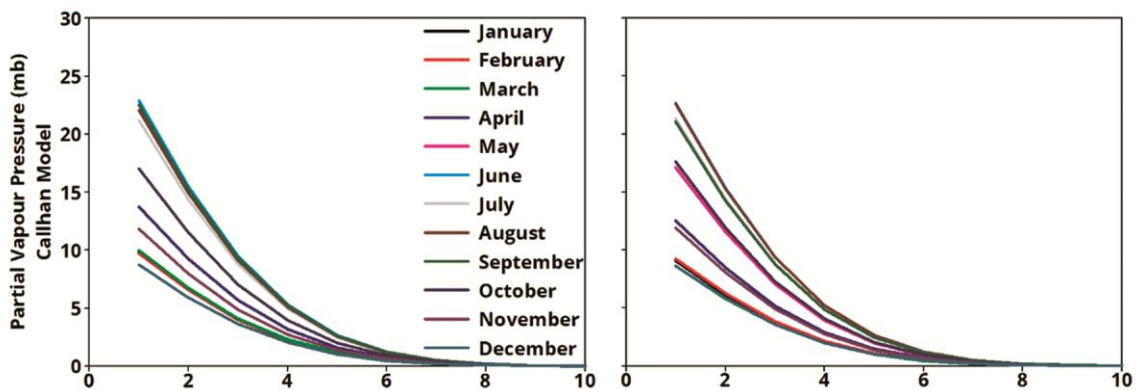


Fig. 5 — Partial vapour pressure (mb) estimated against different Altitudes for Dehradun at Day Time (Left Panel) and Night Time (Right Panel)



(Contd.)

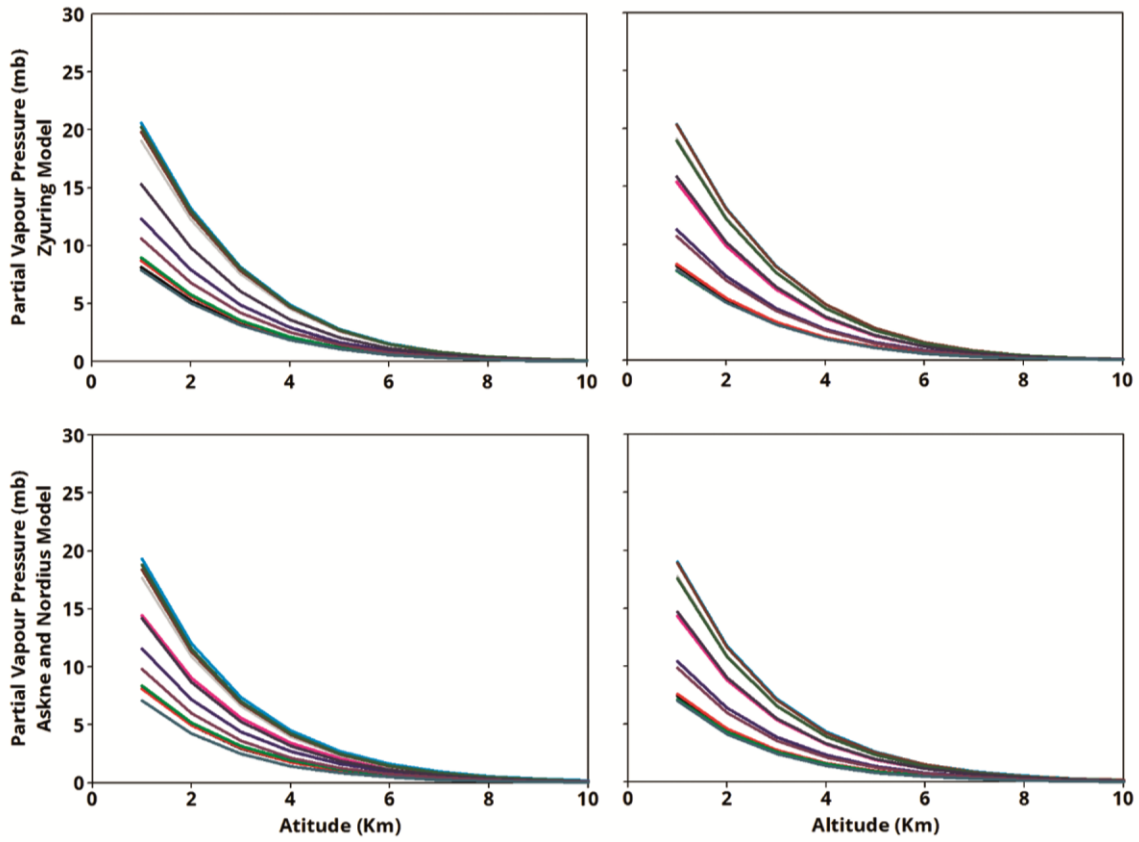
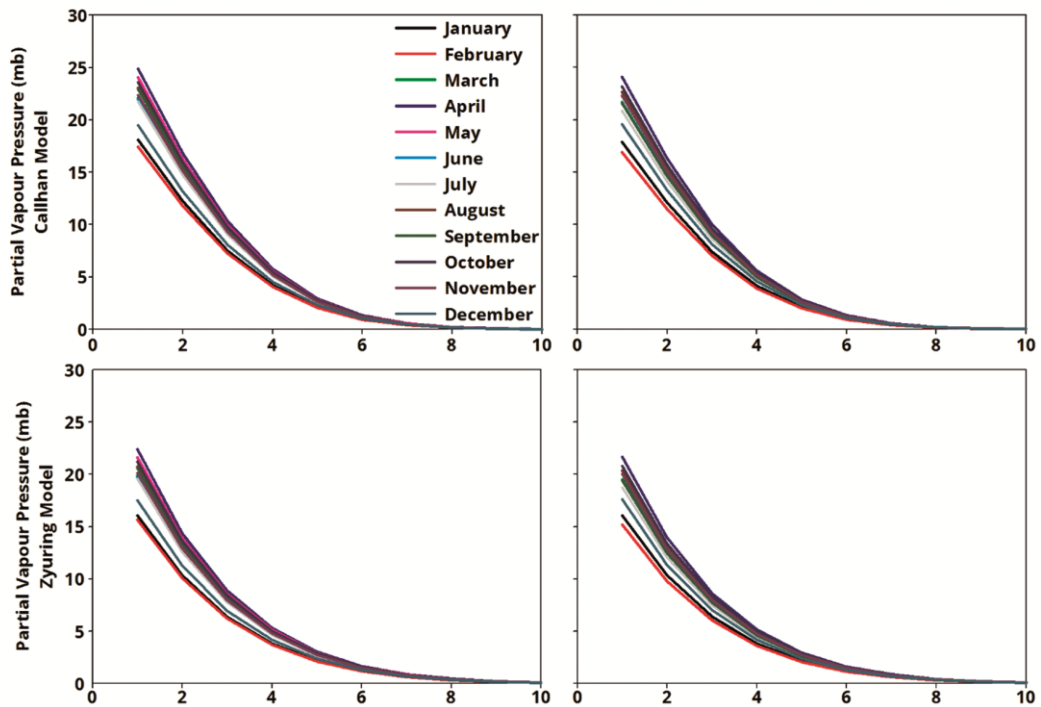


Fig. 6 — Partial vapour pressure (mb) estimated against different Altitudes for Ahmedabad at Day Time (Left Panel) and Night Time (Right Panel)



(Contd.)

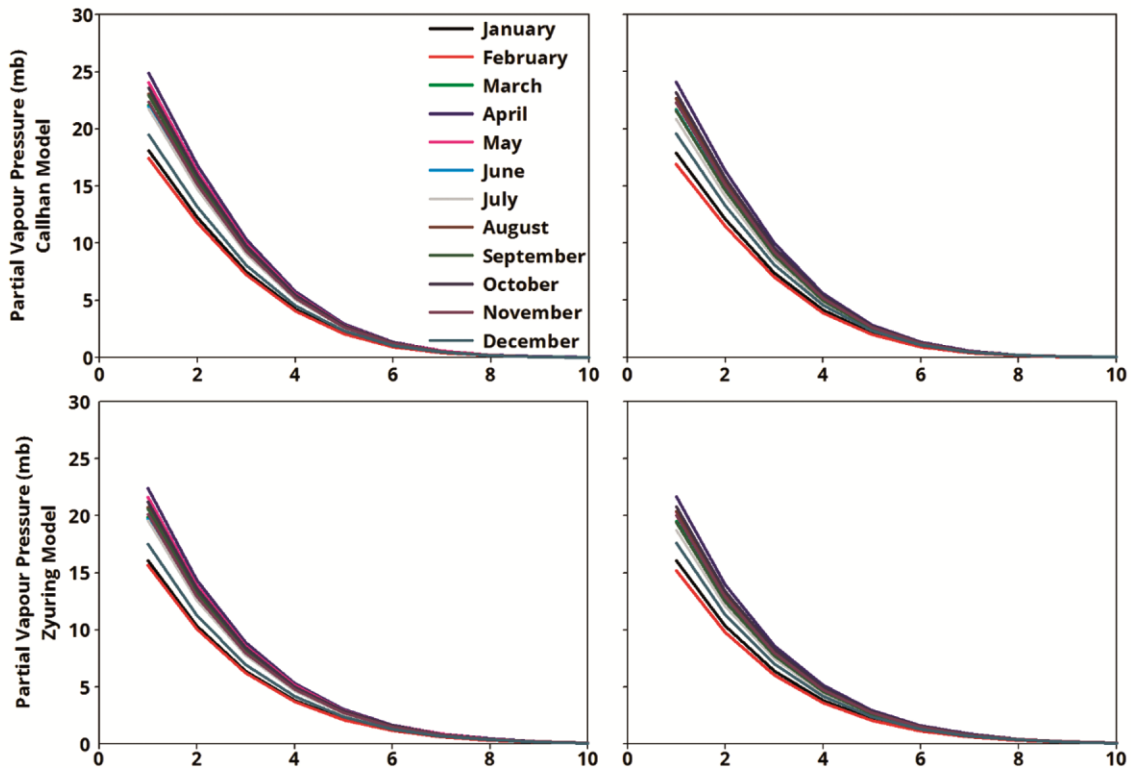
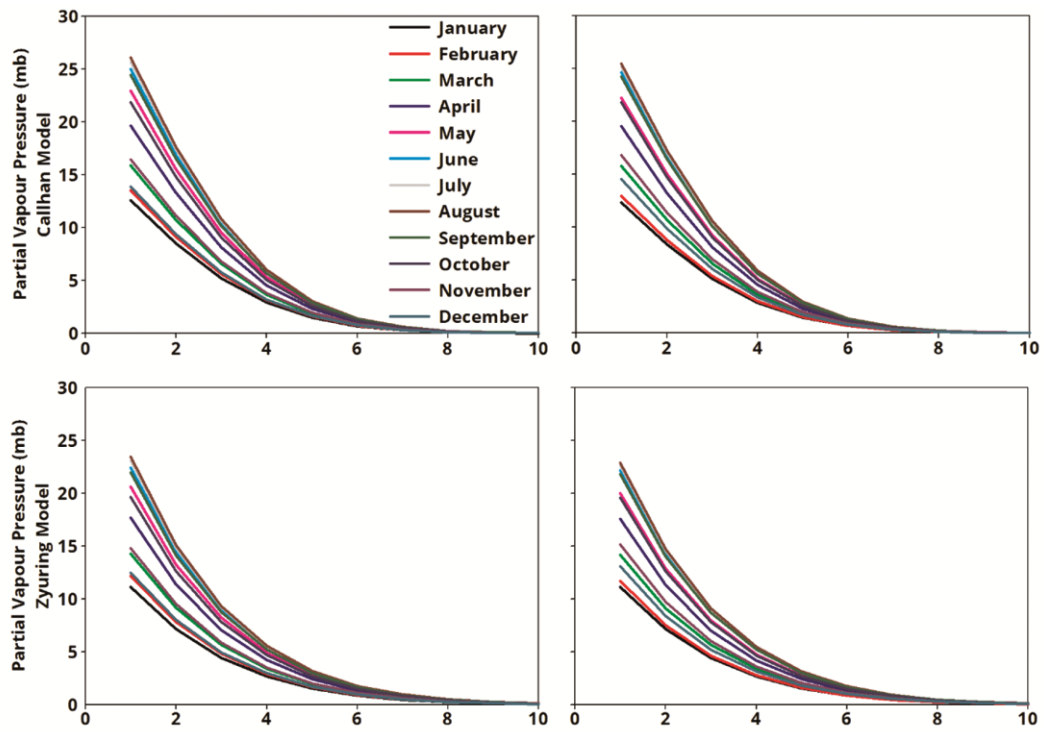


Fig. 7 — Partial vapour pressure (mb) estimated against different Altitudes for Cuddalore at Day Time (Left Panel) and Night Time (Right Panel)



(Contd.)

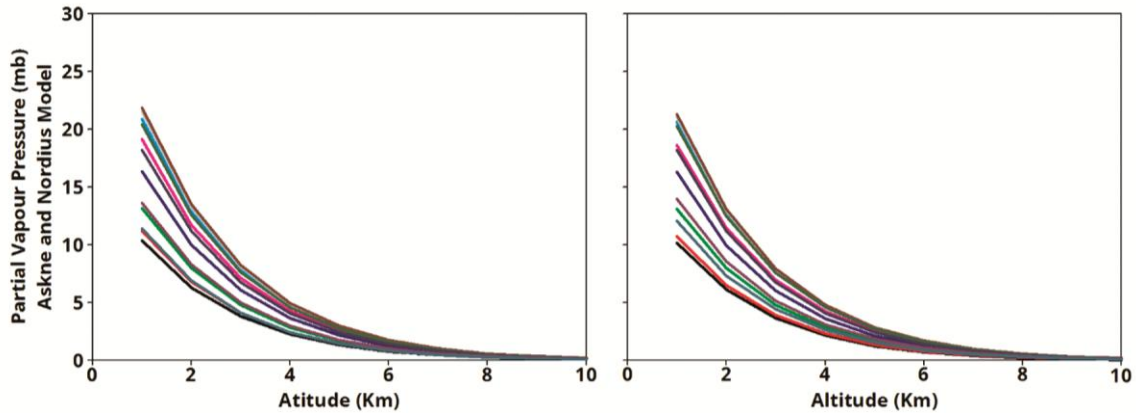


Fig. 8 — Partial vapour pressure (mb) estimated against different Altitudes for Karimganj at Day Time (Left Panel) and Night Time (Right Panel)

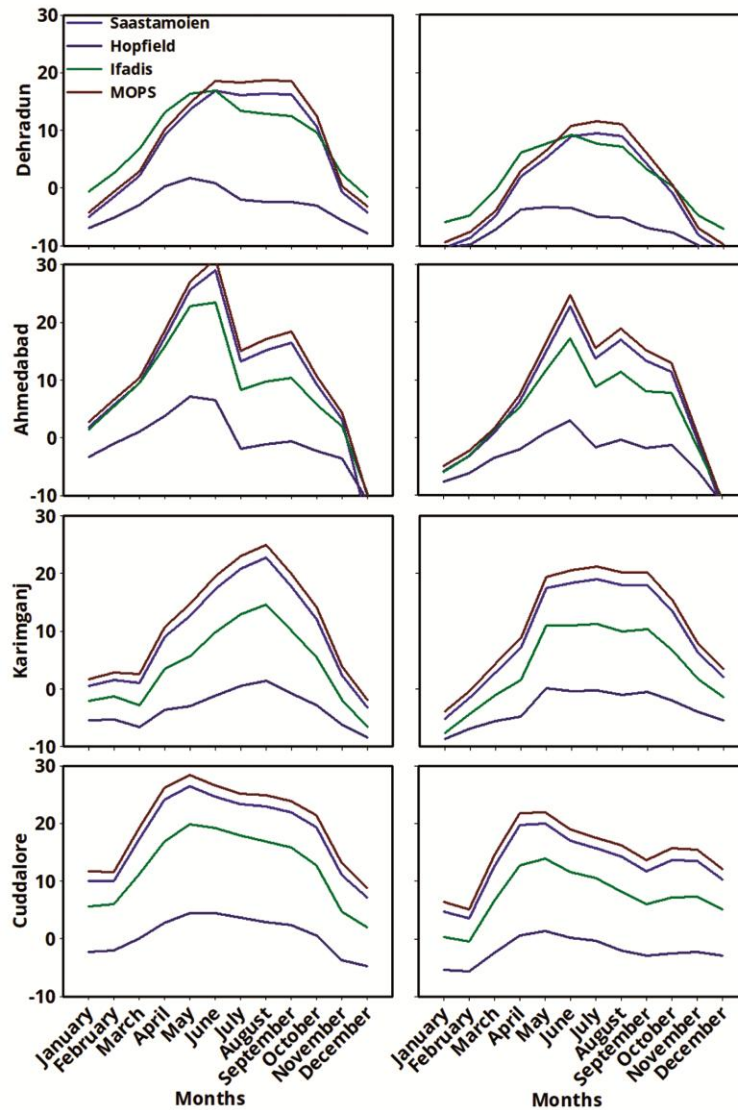


Fig. 9 — Difference in wet delay with NIM (mm) at Day Time (Left Panel) and Night Time (Right Panel)

Table 5 — Error statistics of various models in Zenith wet delay (mm) estimation

		Day Time				Night Time			
		Saastamoinen	Hopfield	Ifadis	Berman	Saastamoinen	Hopfield	Ifadis	Berman
		Mendes	MOPS	Chao	Callhan	Mendes	MOPS	Chao	Callhan
DEHRADUN	Mean	7.474	-2.951	8.702	53.500	-0.433	0.254	1.512	41.913
	RMS	11.219	4.138	10.720	59.660	7.553	4.513	5.994	47.238
AHMEDABAD	Mean	10.950	-0.511	8.759	55.362	6.531	-3.142	4.175	50.137
	RMS	15.601	4.645	12.406	60.059	12.028	4.927	8.874	55.949
CUDDALORE	Mean	18.183	0.718	12.412	79.897	13.078	-1.993	7.444	73.697
	RMS	19.328	3.165	13.808	80.742	13.961	2.887	8.582	74.378
KARIMGANJ	Mean	9.554	-3.427	3.941	66.331	10.975	-2.809	5.118	69.037
	RMS	12.833	4.500	7.709	69.848	13.236	3.719	7.626	71.688
DEHRADUN	Mean	124.101	8.913	73.259	48.886	113.653	0.927	56.127	41.460
	RMS	124.438	12.552	95.295	53.691	113.950	7.977	72.699	45.201
AHMEDABAD	Mean	129.993	12.639	66.945	48.694	123.270	7.897	63.404	46.017
	RMS	130.645	16.531	80.927	52.043	123.824	13.140	79.009	49.993
CUDDALORE	Mean	136.467	20.072	121.494	69.372	129.305	14.959	115.289	65.950
	RMS	136.741	21.148	123.555	69.872	129.450	15.777	117.109	66.375
KARIMGANJ	Mean	125.030	11.329	103.336	60.486	126.802	12.784	107.619	62.427
	RMS	125.412	14.434	113.813	62.892	127.076	14.945	115.768	64.269

delay is observed more in the daytime because in the daytime more partial vapour pressure is observed as discussed earlier. For stations Ahmedabad and Karimganj, slightly more delay is observed in the daytime as compared to night time. For station Cuddalore, the delay is observed almost similar for day and night. From Table 5 also it can be seen that the Hopfield model has less mean error as compared to other models. Since the Hopfield model is very close to NIM results and it has consistency for all the stations, this can be considered as the best model and further can be used for tropospheric delay estimation over Indian conditions. Mendes, Chao, Berman, and Callhan models are also used for tropospheric delay estimation but their estimated values are far away from results. Saastamoinen, Ifadis, and MOPS results show good approximation to NIM values but still have less accuracy as compared to Hopfield results. Difference statistics of these models delay values with NIM models results are also shown in Table 5.

Because of the large differences, the results are not included in Fig. 9. Younes has also performed a similar analysis and found the Saastamoinen model is more suitable for wet delay estimation under variable atmospheric conditions of Egypt²⁰. He has shown that wet delay derived using the Saastamoinen model has mean and RMS error of 11 mm and 3.12 mm with the NIM model.

From the study, it is also observed that in monsoon session tropospheric delay increases as the increment in partial vapour pressure. Station Cuddalore has the highest partial vapour pressure values as the station is very near to the ocean. Station Karimganj has second place among the studied stations where the partial vapour pressure is more. Stations, Dehradun and Ahmedabad having a moderate partial vapour pressure. It is also observed from the analysis that in daytime partial vapour pressure value is slightly more as compared to night time. For the station Cuddalore maximum, the tropospheric delay is observed 296.93

mm in the daytime while the minimum delay is 212.7 in night time. It is also observed that there is not much variation in delay throughout the year. Station Dehradun has minimum 112.52 mm delay in January and the maximum 323.09 mm delay in August. In station Karimganj maximum delay is observed 313.21 mm in August and the minimum delay is observed 159.86 mm in January. Since August is part of the monsoon session more delay is observed in monsoon session over stations Dehradun and Karimganj. In station Ahmedabad maximum delay is observed 273.75 mm while the minimum is observed 108.9 mm. Station Ahmedabad receives less rainfall as compare to other stations so delay observed is less.

5 Conclusion

The present study has been carried out to assess the accuracy of different models for wet tropospheric delay and its associated parameters. Since various navigation systems are operational over the Indian region, the signal of these systems experiences delays when it passes through the earth atmosphere. The wet delay is the part of the total tropospheric delay and is directly related to the water vapour content present in the atmosphere. Saturation water vapour pressure is estimated using Tetten, Magnus, Buck, Wexler, Bolton, and Goff-Gratch model. From the result and analysis, it is shown that the Wexler model has a very less mean error and it can be considered a more suitable model for predicting saturation vapour pressure. A further prediction of partial vapour pressure is carried out using the Wexler model. The distribution of partial vapour pressure with the heights is estimated by Callahan, Zyuring, and Askne and Nordius (both temperature and pressure based) models. The results show that the Zyuring model has a less mean error and more suitable model for predicting the vapour pressure at different height over the region. Finally, the wet tropospheric delay is estimated using Saastamoinen, Hopfield, Ifadis, Berman, Mendes, MOPS, Callahan, and Chao's models. After estimation, the mean error of Hopfield is found to be less than other models which provide within 4 mm difference. So it is considered as the best model among all models for wet delay prediction. Some of the places Saastamoinen and Bolton models also closely matched the Hopfield results. So these models also can be used for wet delay estimation.

From the analysis, it is found that Wexler, Zyuring, and Hopfield models are best models for predicting saturation vapour pressure, the vertical profile of

partial vapour pressure and wet tropospheric delay respectively for Indian conditions. Further, these models also can be evaluated with real datasets. Considering this analysis for tropospheric delay, corrections can be made into GNSS signals to obtain better accuracy.

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